ASTRONOMY and PARTICLE PHYSICS

Mike Luciuk

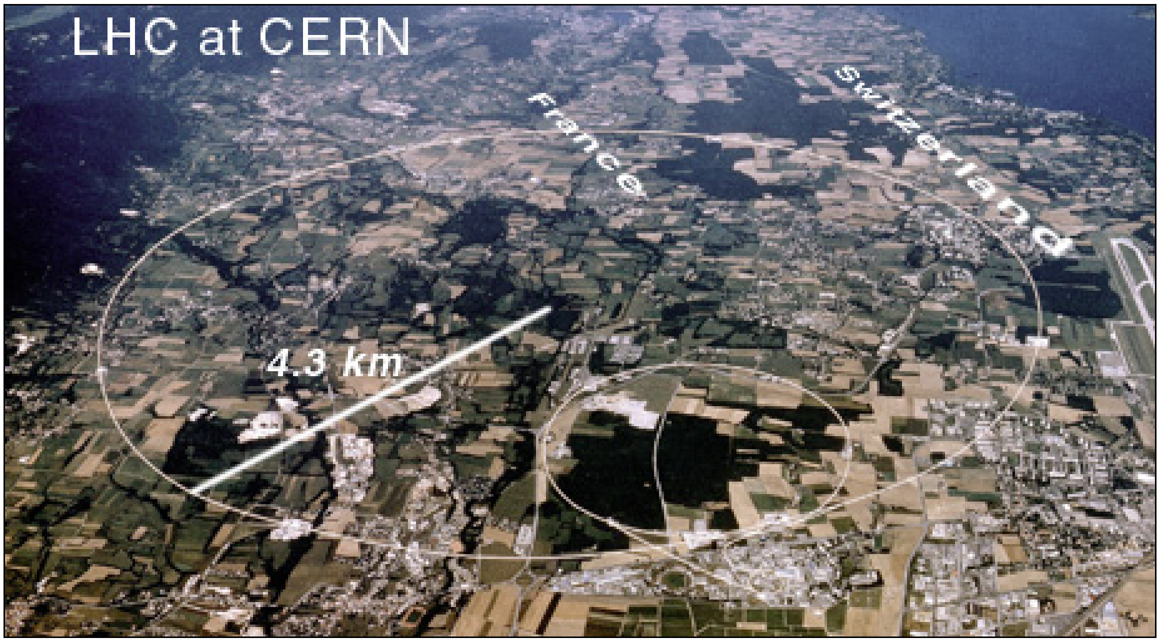


Figure 1. The CERN Large Hadron Collider spans across two countries
http://www.atlas.ch/etours_accel/etours_accel03.html

1. INTRODUCTION

Astronomy is without a doubt one of the oldest sciences. The observations of the Babylonians and Egyptians, the measurements of the Greeks and Arabs, and the theorists and experimenters of Europe were essential stepping stones to astronomy up through the nineteenth century. However, it was the discoveries in physics early in the twentieth century, giving rise to astrophysics that have added much to our understanding of galaxies and stars. It’s interesting that astronomy, the study of the very large has been so greatly complimented by nuclear research, the study of the very small. Particle physics is very much being utilized in today’s astronomical research. This article will outline some particle physics background, and astronomical areas in which this branch of science has played a key part.

Figure 1 illustrates the size of CERN’s Large Hadron Collider (LHC) as it extends underground beneath France and Switzerland. The LHC is currently in the process of testing its various components before being able to deploy colliding high energy protons in the search for the Higgs and supersymmetric particles, with the goal of further understanding the nature of nuclear particles. Possibly, sometime in 2009, we will hear news of new discoveries that enhance our knowledge of nuclear physics and astronomy. A detailed discussion of particle accelerators and CERN’s LHC appears at the end of this paper.

2. PARTICLE PHYSICS OVERVIEW

In this section we'll cover, broadly but lightly, some aspects of particle physics. This background will be useful for understanding some details in sections 3 on "Astronomy and Particle Physics" and section 4 on "Particle Accelerators".

2.1 SOME PARTICLE PHYSICS HISTORY

Although the Greek Democritus (460-370 BC) believed that the smallest indivisible piece of matter was an atom, it was the work of chemists and physicists in the nineteenth and twentieth centuries that demonstrated their existence. In 1803, John Dalton (1766-1844) used atoms to explain why chemical compounds always contain the same mass ratios of their elemental components. In 1861, Gustav Kirchhoff (1824-1887) and Robert Bunsen (1811-1899) established that spectra are unique to each element. By 1865, James Maxwell's (1831-1879) equations unified electric and magnetic fields into electromagnetism. In 1869, Dmitri Mendeleev (1834-1907) classified known elements into the Periodic Table. Natural radioactivity was discovered by A. H. Bequerel (1852-1908) in 1896 when uranium was found to emit mysterious alpha, beta and gamma "rays". The following year, J. J. Thompson (1856-1940) discovered the electron. Since electrons are negatively charged, and, since matter was known to be electrically neutral, it was logical to assume atoms also had a positively charged component. The Curies (Figure 2) discovered polonium and radium in 1898. Two years later, M. Planck (1858-1947) proclaimed that electromagnetic radiation was emitted only in quantized form. Einstein's (1879-1955) special relativity and photoelectric research was published in 1905. In 1911, Ernest Rutherford (1871-1937) discovered that the atom had a tiny, massive nucleus with a positive charge, identifying the proton that provided the neutrality of an atom. Two years later, Niels Bohr (1885-1962) used quantum ideas to model atoms. When Rutherford bombarded nitrogen with alpha particles in 1919, he discovered protons were emitted, creating artificial radioactivity. In 1932, J. Chadwick (1891-1974) discovered the neutron and C. Anderson (1905-1991) discovered the positron, the anti-particle of the electron.

Over the next decades many new particles like mesons were discovered. Particle theory evolved into making predictions and adapting to new discoveries. Particle accelerators and detectors were key discovery tools.

Figure 2. MARIE (1867-1934) and PIERRE CURIE (1859-1906)
http://lutece.fnal.gov/Talks/RevolutionsVLC.pdf

Two theoretical concepts in the twentieth century were necessary to come up with what is known as the Standard Model (SM) of particles. Albert Einstein's special theory of relativity in 1905 was a key development. As well as postulating the maximum speed of light (c = 299,792 km/s) in vacuum, it equates mass with energy via the most famous equation in physics,

$$E = mc^2 \tag{1}$$

The other major development was the concept of quantum mechanics. This area was pioneered by M. Planck (1858-1947) in 1897, Einstein in 1905, N. Bohr (1885-1962), L. de Boglie (1882-1987), E. Schrödinger (1887-1961), and W. Heisenberg (1901-1976). Quantum mechanics deals with the very small, where certain processes occur in discrete rather than continuous amounts. It postulates that *both* a particle's position and momentum cannot be exactly determined (Heisenberg's Uncertainty Principle) and matter can exhibit the properties of a wave. The larger a particle's momentum, the smaller its wavelength and the more wave-like its properties. By the late twentieth century the Standard Model of particle physics was well established, but it provided no explanation for the differing masses of particles. The inability to include gravity into its framework has led physicists to new directions. Currently, multi-dimensional String Theory is being explored as a "Theory of Everything."

2.2 THE FOUR FORCES of NATURE

By the last half of the twentieth century, theoretical and experimental activity was able to discover the identity and characteristics of the fundamental particles of nature, those that make up the atoms. These will be covered a little later. First, we should address the four known forces of nature in order of increasing strength (Table 1):

1. **Gravity**. We're all familiar with the force of gravity from personal experience. Newton, in the early eighteenth century, and Einstein, early in the twentieth century, described gravity in different ways: Newton as a force and Einstein as geometry in space-time. Although gravity is a powerful force, its impact at nuclear distances is dwarfed by the other forces encountered, so it has no role in particle physics.
2. **Weak Nuclear (Electroweak) Force**. This short range force operates within the nucleus of an atom. It can convert a neutron to a proton in the nucleus, thereby emitting an electron (beta particle) and an anti-neutrino. This form of radioactivity will be covered in more detail later.
3. **Electromagnetism**. Radiation ranging from radio waves to gamma rays and magnetism are familiar aspects of electromagnetism. Late in the nineteenth century, Maxwell was able to describe electromagnetism mathematically and he determined that all forms had the same velocity, c = 299,792 km/s. An important aspect of electromagnetism is the electrostatic force that exists between charged particles. This force plays an important role in particle physics because of its long effective range.
4. **Strong Nuclear Force**. This very short range force within the nucleus plays a role in keeping the positively charged protons confined within the nucleus. It also keeps the constituents within protons and neutrons (quarks) contained. The strong force is 10^{38} times stronger than the gravitational force and it is 100 times stronger than the electromagnetic force.

The particles that are the means by which these forces are able to act are called *bosons*. The gravitational boson is a hypothetical particle called a *graviton* which has not yet been observed. The weak force is mediated by three different particles, the W^+, W^-, and Z bosons. Massless *photons* are the electromagnetic bosons. Eight particle-like *gluons* mediate the strong force.

FORCE	BOSONS	RELATIVE STRENGTH	RANGE (meters)
GRAVITY	gravitons	1	infinite
WEAK NUCLEAR	W^+ W^- Z	10^{25}	10^{-18}
ELECTROMAGNETIC	photons	10^{36}	infinite
STRONG NUCLEAR	gluons	10^{38}	10^{-15}

TABLE 1. The Four Forces in Nature

2.3 ELEMENTARY PARTICLES

There are twenty-four elementary particles, consisting of six leptons and six quarks, plus an equal number of their antiparticles. *Leptons* are elementary negatively charged point-like particles that have no apparent structure. The six leptons in Table 2 also have identical anti-particles with opposite charge. Muon and tauon particles are not stable.

particle	symbol	mass (MeV/c^2)	charge (e)	spin
electron	e^-	0.511	-1	$\frac{1}{2}$
electron neutrino	ν_e	> 0	0	$\frac{1}{2}$
muon	μ	105.7	-1	$\frac{1}{2}$
muon neutrino	ν_μ	> 0	0	$\frac{1}{2}$
tauon	τ	1780	-1	$\frac{1}{2}$
tauon neutrino	ν_τ	> 0	0	$\frac{1}{2}$

TABLE 2. The Leptons
http://scienceworld.wolfram.com/physics/Lepton.html

Table 3 lists the six quarks, which also have identical anti-particles of opposite charge. They do not have measurable size or internal structure. Quarks are not found in isolation.

	flavor	mass (eV/c^2)	charge (e)	spin ($\hbar$)
u	up	5 M	$\frac{2}{3}$	$\frac{1}{2}$
d	down	7 M	$-\frac{1}{3}$	$\frac{1}{2}$
s	strange	150 M	$-\frac{1}{3}$	$\frac{1}{2}$
c	charmed	1.5 G	$\frac{2}{3}$	$\frac{1}{2}$
t	top	176 ± 13 G	$\frac{2}{3}$	$\frac{1}{2}$
b	bottom	4.8 G	$-\frac{1}{3}$	$\frac{1}{2}$

TABLE 3. The Quarks
http://scienceworld.wolfram.com/physics/Quark.html

Charges carried by quarks are fractional, not unit sized as with leptons. Quarks are the components of protons and neutrons, called *hadrons* in an atom's nucleus. Hadrons are particles made up of three quarks. The quark components in a proton are up-up-down (uud), which results in a charge of +1e. The quark components of a neutron are up-down-down (udd) which results in its neutral charge. As mentioned previously, a neutron in a nucleus may change to a proton under the weak force, when one of its down quarks changes to an up quark. Quark-antiquark pairs are called *mesons*. For example, a positive charged pion, is made up of an up quark and an antidown quark with a mass of 139.6 MeV and a mean life of 2.6 x 10^{-8} seconds. (See relationship of mass to electron volts below.)

An attribute that all particles have is *spin*, a quantum effect indicating intrinsic angular momentum. These particles do not actually rotate. The spin occurs in discrete amounts of *reduced Planck's constant*, h-bar (1.0546 x 10^{-34} Js). Bosons carry integer spins. For example, photons have spin 1, while gravitons have spin 2 (2h-bar). Mesons also have integer spins. Particles that have half-integer spins like leptons, quarks, and hadrons are called *fermions*. For example, electrons have spin ½ (½h-bar).

2.4 USEFUL DEFINITIONS and RELATIONSHIPS

Relating Mass to Electron volts (eV)

An electron volt is a measure of energy used in particle physics. It's defined as the work required to accelerate an electron through one volt potential difference. This is a tiny amount of energy, 1.602 x 10^{-19} joules. Using Einstein's mass-energy equation (equation 1), the electron volt is useful as a measure of particle mass. For example, the mass of an electron is 9.109 x 10^{-31} kg. Therefore, the equivalent mass in electron volts would be 9.109 x 10^{-31} x $(299{,}792{,}000)^2$ / 1.602 x 10^{-19} = 511,032 eV or 0.511 MeV. Often, the electron volt mass includes the c^2 divisor so the mass of an electron is written as 0.511 MeV/c^2. Similarly, the mass of a proton is 938.3 MeV/c^2, and of a neutron 939.6 MeV/c^2. At the other end of the particle mass scale, the estimated mass of neutrinos is only about 0.3 eV/c^2.

Another common particle physics mass designation is the *atomic mass unit, u*. It's also known as a *dalton, Da*. It's defined as one twelfth the mass of a carbon 12 atom (6 protons and 6 neutrons). This has a value of 1.66 x 10^{-27} kg, or 931.5 MeV.

Pair production and Pair Annihilation

Although they are massless, photons have energy and momentum. Photon energy varies as frequency or inversely as wavelength. High energy photons like gamma rays, can create particles via $E = mc^2$ or $m = E/c^2$. Recall that the mass of an electron is 0.511 MeV. Therefore, a photon with energy 2 x 0.511 MeV = 1.022 MeV can create an electron/positron pair, each with a mass of 0.511 MeV. Conservation of charge is maintained by the creation of a particle/antiparticle pair. Also, if an electron and a positron (anti-electron) meet, they will create a photon of 1.022 MeV energy by their annihilation. Such is the wonder of particle physics.

Relating Energy and Temperature

Recall that temperature is not a measure of heat. It's a measure of particle kinetic energy. The average kinetic energy, E of particles in MeV relating to temperature, T in Kelvin is

$$E = kT \tag{2}$$

Where k (Boltzmann's constant) = 8.62×10^{-11} MeV/K. We can then relate the temperature equivalent to energy for a pair production. For example, an electron/positron pair is created with a photon of 1.022 MeV energy. The temperature for this process would be $1.022/(8.62 \times 10^{-11}) = 1.19 \times 10^{10}$ K.

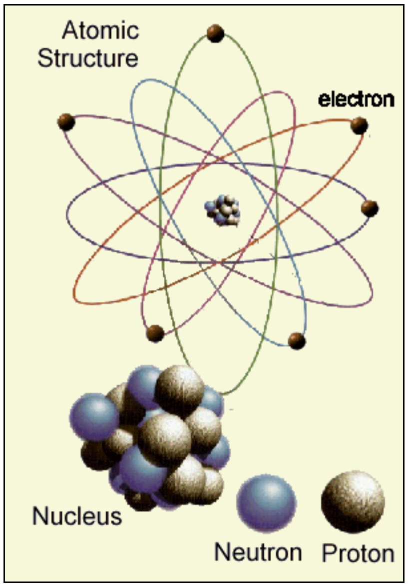


Figure 3. Atomic Structure (highly simplified)
www.users.bigpond.com/.../fission/Fission2.html

2.5 ATOMIC STRUCTURE

An atom is made up of three particles: negatively charged electrons and a nucleus consisting of positively charged protons (uud quarks), and neutrons (udd quarks), called *nucleons,* except for hydrogen which has only a proton in its nucleus. The depiction in Figure 3 is simplified and not to scale. The figure shows definite trajectory paths for electrons. However, their paths are actually so probabilistic that electrons form a cloud of various energies around the nucleus. The nucleus is also very much smaller than shown in the figure. The ratio of protons to neutrons in a nucleus varies. The number and arrangement of electrons in an atom (with the same number of protons in its nucleus) determines the element's chemical properties, and determines its *atomic number Z*. The sum of the protons and neutrons in its nucleus is called an element's *mass number A*. An atom can become charged by acquiring or losing electrons. The atom would then carry a negative or positive charge respectively, and is said to be *ionized*.

Hydrogen is the simplest atom. It consists of one electron orbiting a single proton in its nucleus. An isotope of hydrogen, deuterium, also has a neutron as well as a proton in its nucleus. Isotopes have differing numbers of neutrons in their nuclei and the same Z because they have the same number of protons in their nuclei. They have similar chemical properties. For example, deuterium combines with oxygen to form heavy water, D_2O. Heavy water is 10% more dense than H_2O, has higher freezing and boiling points and is somewhat poisonous. The naturally occurring atom with the most nuclear protons is uranium. Its most common isotope, U-238, has 92 electrons and an unstable nucleus consisting of 92 protons and 146 neutrons. Uranium also has two more naturally occurring isotopes, U-234 and U-235 with 142 and 143 neutrons respectively in their nuclei. As the proportion of neutrons to protons in a nucleus differs from 1:1, an atom's nucleus can become unstable and radioactivity may occur.

Nuclear Binding Energy

Recall that an atom's nucleus is made up of positively charged protons and neutral neutrons, all bound by the strong nuclear force. The mass of the nucleus is always smaller than the sum of the masses of its constituent protons and neutrons. This mass difference is a measure of the binding energy holding the nucleus together. Figure 4 is a graph of the nuclear binding energies for the elements. Note that the binding energy rises until it peaks at iron after which it gradually falls. This means that when lighter nucleons than iron combine to form heavier nucleons, energy is released, a process called *fusion*. Energy must be supplied for nucleons heavier than iron to fuse. Also, when nucleons heavier than iron break into smaller nucleons, energy is released, a process called *fission*.

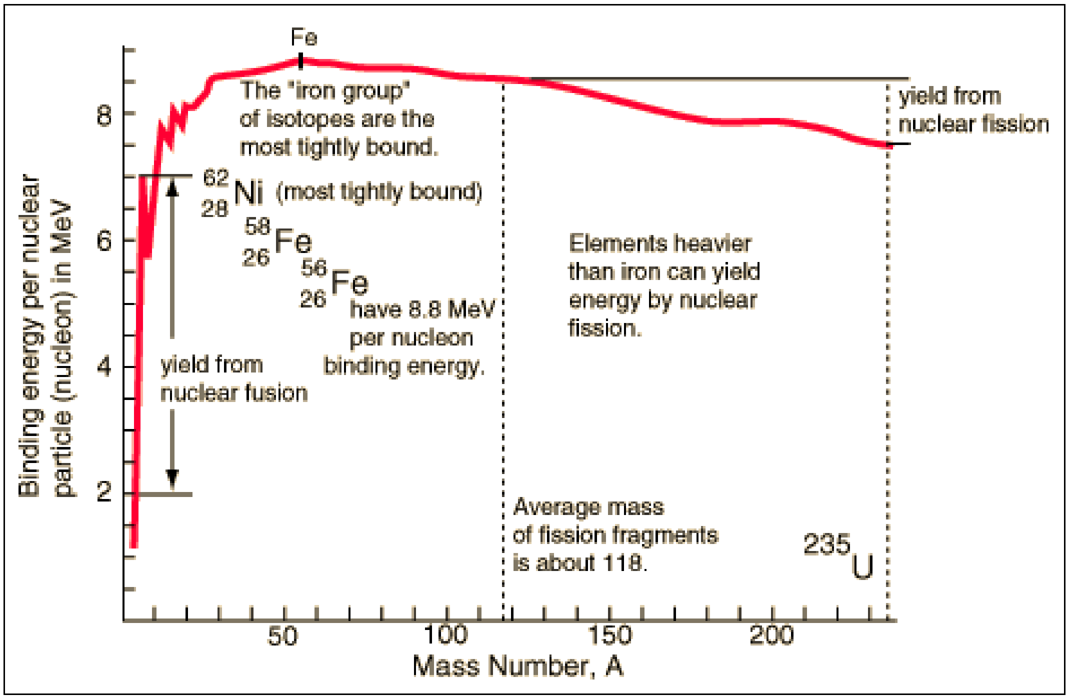


Figure 4. Nuclear Binding Energy
http://hyperphysics.phy-astr.gsu.edu/hbase/nucene/nucbin.html#c2

2.6 RADIOACTIVITY

An atom's unstable nucleus can lose energy by emitting radiation in the form of particles (alpha or beta for example) or electromagnetic energy (gamma radiation). See Figure 5 for the penetrating capability of these radiation forms. The accepted measure of radioactive decay is the *Becquerel*, one decay per second. An alpha particle is a helium nucleus with a ++ charge, consisting of two protons and two neutrons. When an atom emits an alpha particle, the original atom loses two Z's (protons) and four A's (nucleons). A beta particle is an electron formed when a neutron within the nucleus is converted to a proton. When an atom emits a beta particle, the original atom gains one Z (proton) with its A remaining the same. No Z or A changes occur with the nuclear emission of gamma rays, high energy photons.

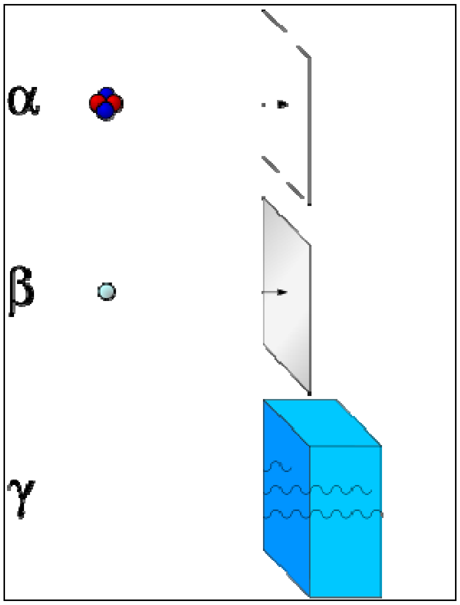


Figure 5. Radiation Penetration Capability
Alpha particles may be completely stopped by a sheet of paper, beta particles by aluminum shielding. Gamma rays can only be reduced by much more substantial barriers, such as a very thick layer of lead.
http://en.wikipedia.org/wiki/Radioactive_decay

U-235 has a capability that no other naturally occurring element possesses in economic quantities. It is capable of fission chain reaction. Normally, U-235 decays to Thorium-231 plus an alpha particle. However, if a U-235 atom encounters a neutron, it may convert to U-236, which then splits into two smaller atoms plus several neutrons. This process will result in a runaway chain reaction if the mass of U-235 exceeds a critical mass, which is required to retain sufficient neutrons to keep the reaction going. A huge amount of energy is generated in an instant, resulting in an atomic bomb (see Figure 6). Only 0.72% of naturally occurring uranium is the U-235 isotope, so fission cannot occur without an enrichment process. Weapon-grade U-235 is in the range of 85% purity. The so-called hydrogen bomb utilizes the fusion process, and, as illustrated in figure 6, it has a much greater energy and explosive yield than an atomic bomb. This device utilizes the hydrogen isotopes deuterium and tritium to create helium via fusion.

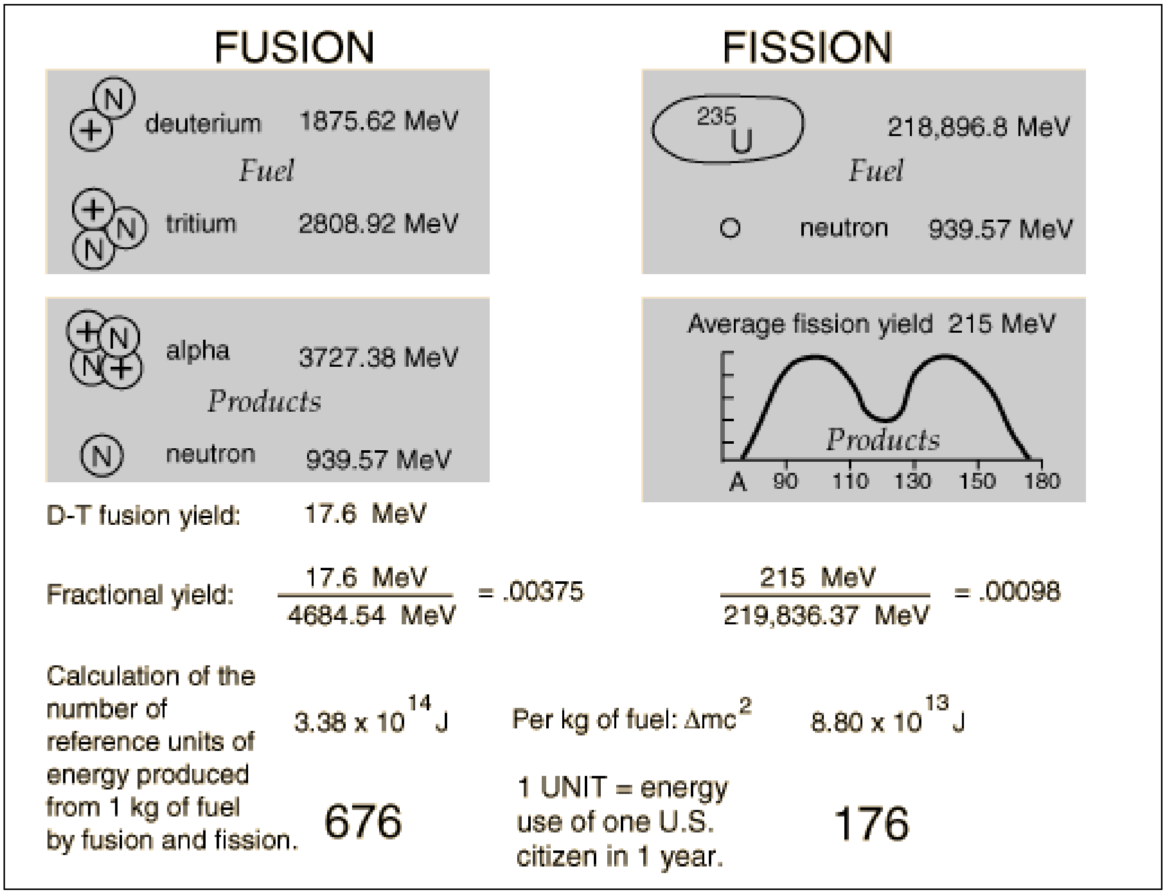
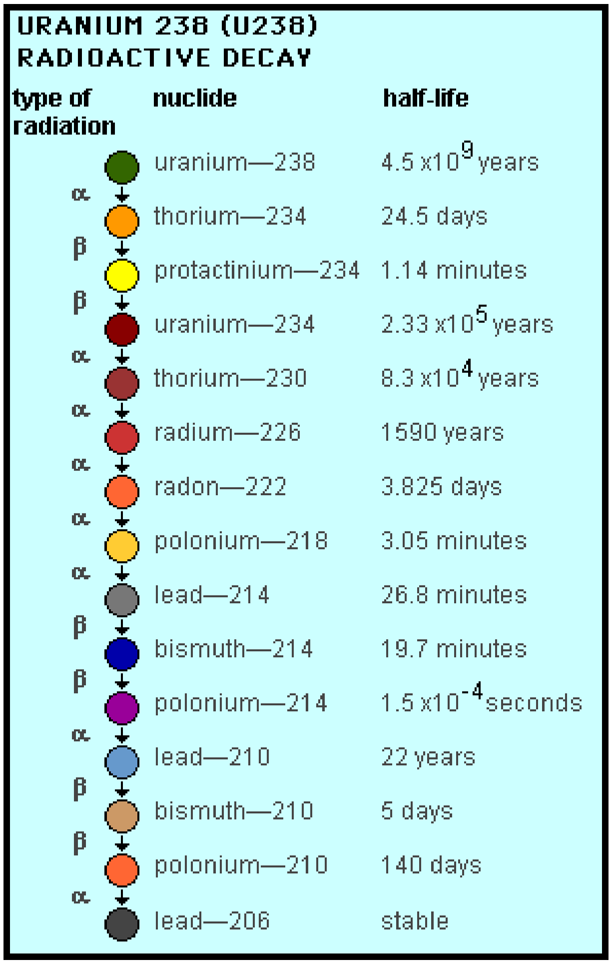


Figure 6. Hydrogen Bomb Fusion & Atomic Bomb Fission
http://hyperphysics.phy-astr.gsu.edu/hbase/nucene/nucbin.html#c4

It’s common to describe radioactivity rates by the term *half-life*. This is the amount of time for a substance to decay to half its initial value. So if a substance has a half-life of $t_{1/2}$ years, after $t_{1/2}$ years only half the original amount would remain. After an additional $t_{1/2}$ years, only ¼ of the original amount would remain. The most common isotope of uranium, U-238, has a half-life of 4.47 billion years. C-14, an isotope of carbon has a half-life of 5,730 years and is well-known for its use in carbon dating. Tritium, an isotope of hydrogen with two neutrons in its nucleus has a half-life of 12.35 years. Radon gas has a half-life of 3.8 days. Some isotopes have very short half-lives, in the sub-microsecond range.

We are exposed to several forms of natural radioactivity as well as some that are derived from human activity. Cosmic rays (mostly high energy protons) possibly emanating from beyond our Milky Way as well as from the Sun are one source. Another is that of long half-life elements that occur on Earth like U-238 and K-40. The radioactive decay of U-238 is the start of a chain of decays that end when the final product is a stable isotope of lead (Figure 7).



URANIUM 238 (U238)
RADIOACTIVE DECAY

type of radiation	nuclide	half-life
	uranium—238	4.5 x10^{9} years
α		
	thorium—234	24.5 days
β		
	protactinium—234	1.14 minutes
β		
	uranium—234	2.33 x10^{5} years
α		
	thorium—230	8.3 x10^{4} years
α		
	radium—226	1590 years
α		
	radon—222	3.825 days
α		
	polonium—218	3.05 minutes
α		
	lead—214	26.8 minutes
β		
	bismuth—214	19.7 minutes
β		
	polonium—214	1.5 x10^{-4} seconds
α		
	lead—210	22 years
β		
	bismuth—210	5 days
β		
	polonium—210	140 days
α		
	lead—206	stable

Figure 7. U-238 Decay Sequence
http://www.atral.com/U2381.html

On-going shorter half-lived sources include radium-226 which is a by-product of uranium, and radon-222, produced from radium. Some radiation comes from coal-ash, which contains traces of uranium, thorium and their daughter products. Radioactivity from atomic above-ground tests prior to the 1963 Limited Test Ban Treaty have decayed significantly, so that it is now of minor consequence. The 1986 nuclear power plant disaster at Chernobyl spread radioactive material across Eastern Europe. Iodine-131 (eight day half-life) was a threat for thyroid cancer. The more local cesium-137 (30 year half-life) deposits have made the town site uninhabitable to this day.

3. ASTRONOMY and ASTROPHYSICS

The fusion mechanism creating stellar energy is a major nuclear process in astronomy. We'll see that these are complex processes that depend on the mass of a star. Another area of particle physics that is important in astronomy is nucleosynthesis, the creation of the heavier elements. After the Big Bang, and prior to star formation, the universe was made up of hydrogen, helium and lithium, plus energy in the form of photons. Heavier elements resulted from the evolution of stars. We'll explore both these processes in some detail.

3.1 BIG BANG NUCLEOSYNTHESIS

It has been determined that the Big Bang, the creation event of our universe, occurred about 13.7 billion years ago. This is consistent with a Hubble constant of 71 km/s/megaparsec. In addition to galaxy redshifts varying with distance, the existence of the 2.275 K cosmic microwave background (CMB) radiation is evidence for the Big Bang. It's thought that at inception, the universe began as a point with unimaginatively great temperature and pressure immediately followed by rapid expansion that continues to the present. Figure 8 illustrates the expansion with the galaxies moving apart with time, like raisins in a loaf of rising bread.

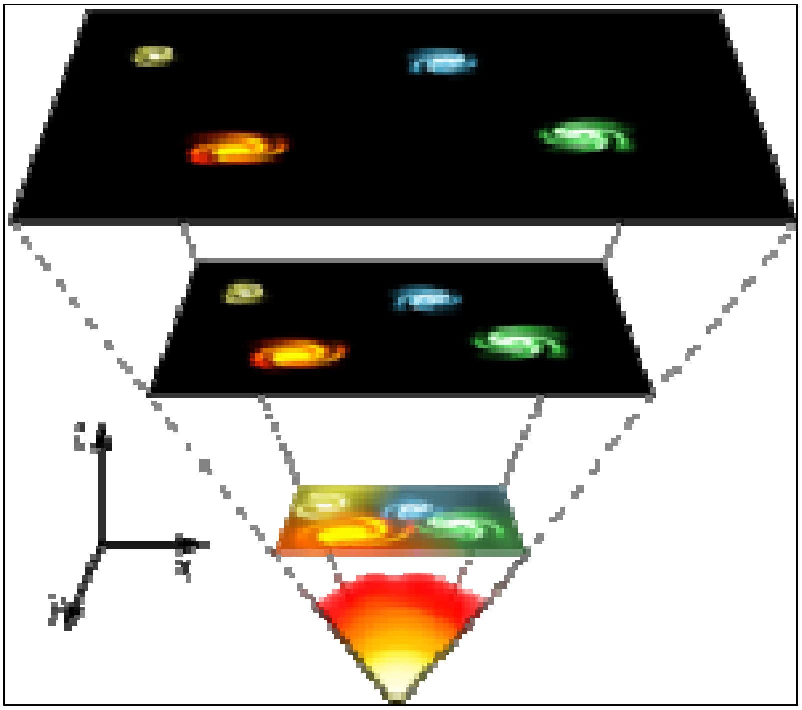


Figure 8. Expansion of the Universe
http://en.wikipedia.org/wiki/Big_Bang

At inception, it's thought that temperatures reached 10^{32} K, followed by rapid cooling as expansion progressed. Initially, there existed a mixture of quark/gluons, leptons, and photons. After about 0.01 milliseconds, protons and neutrons were created from the quarks. After about three minutes, at a temperature of 10^{9} K, light ionized elements began to be formed by nuclear fusion. They were mostly hydrogen (75%), helium (25%), and tiny amounts of deuterium and lithium. A great mystery is that theory predicts equal amounts of matter and anti-matter which would annihilate each other into photons. However, it's thought that the ratio of matter to anti-matter was about 100,000,001 to 100,000,000, which is why no significant ant-matter exists in the universe.

As cooling and expansion continued for about 380,000 years the temperature cooled to 3,000 K. Protons and electrons formed neutral hydrogen causing the universe to become transparent. The cosmic microwave background could now moves freely. Matter formed into dark matter clumps and stars begin to evolve after 100-200 million years. Heavier elements were created in supernovae from the earliest stars. Finally, dark matter, stars and gas formed the first galaxies.

3.2 NUCLEOSYNTHESIS in STARS

Recall that in the main sequence of the of the Hertzsprung-Russell (H-R) diagram (Figure 9), stars convert their hydrogen to helium. There are a number of processes that dominate, which depend on the mass of the star. The most important process for stars about the size of our Sun is the proton-proton or p-p cycle. Hotter massive stars depend more on the carbon-nitrogen-oxygen or CNO cycle. The enormous pressure and temperature in the core of stars enable these processes to operate in spite of the electrostatic repulsion of like charged ions.

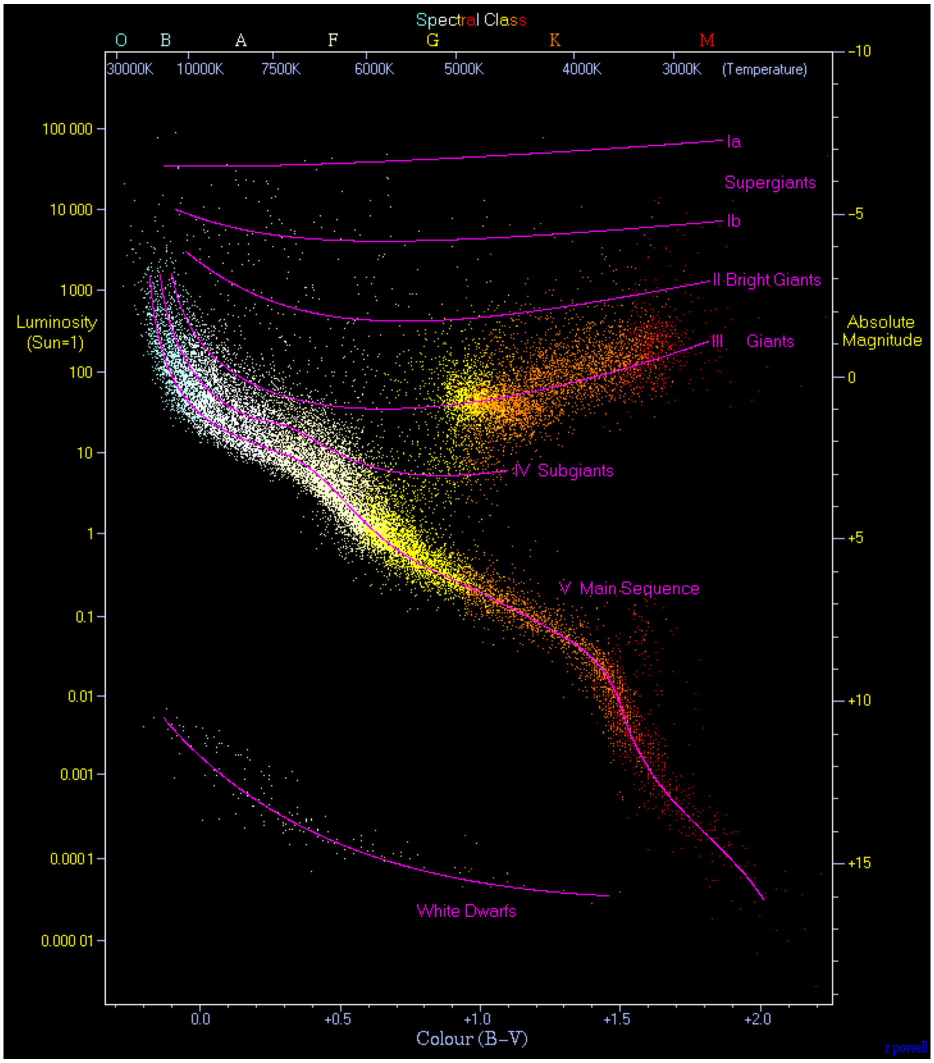


Figure 9. Hertzsprung-Russell Diagram
http://en.wikipedia.org/wiki/Hertzsprung-Russell_diagram

Proton-Proton Chain

There are three p-p chains to be in effect. We'll cover only the most important one utilized by the Sun, in which hydrogen is converted to helium thereby releasing energy by Einstein's E = mc^2 equation.

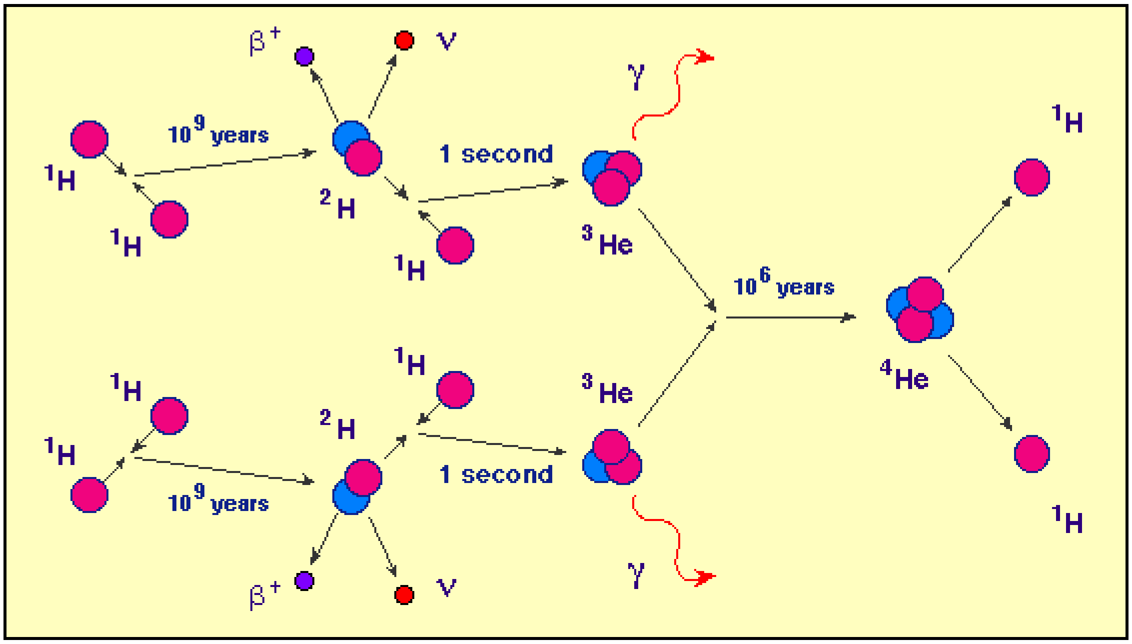


Figure 10. Main Branch P-P Chain
(protons are red, neutrons are blue)
http://csep10.phys.utk.edu/astr162/lect/energy/ppchain.html

Figure 10 illustrates the main branch p-p chain and indicates average times to complete each part of the process. The superscripts indicate the mass number of the particles. The ultimate net result is:

$$4\,^1H \rightarrow {}^4He + 2\beta^+ + 2\upsilon + 2\gamma + 26.7MeV$$

Note that a half-life of a billion years is required for the first step. This is because the Coulomb electrostatic forces are so difficult to overcome by the two positively charged protons. The four hydrogen ions (protons) are 0.7% more massive than the resulting helium ion. That mass difference is converted to 26.7 MeV of energy.

Carbon-Nitrogen-Oxygen (CNO) Cycle

Massive stars can convert hydrogen into helium by another means because their cores are much hotter. The CNO cycle generates the most of the energy and it operates much faster than p-p. Figure 11 illustrates the CNO cycle. The carbon, nitrogen, and oxygen are not consumed. They act as catalysts. As with the p-p process, the CNO cycle converts hydrogen to helium, but much faster. The net result is similar to the p-p chain:

$$4\,^1H \rightarrow {}^4He + 2\beta^+ + 2\upsilon + 3\gamma + 26.8MeV$$

The ^{13}N to ^{13}C step has a half-life of about 10 million years, as opposed to the p-p half-life of a billion years. As a result, massive stars on the main sequence burn brighter and live shorter lives than less massive stars.

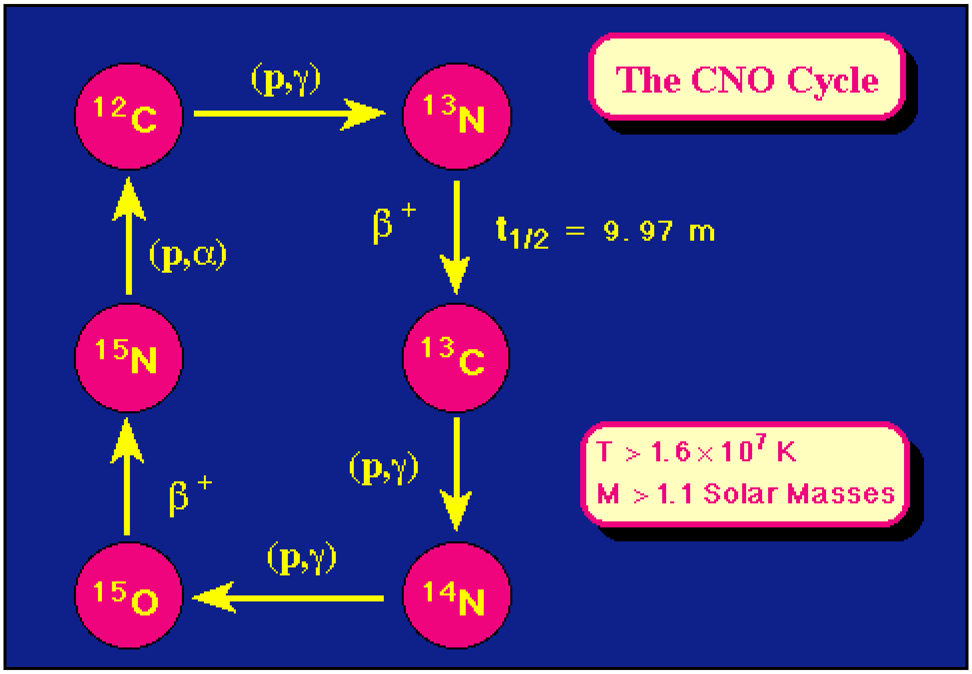


Figure 11. The CNO Cycle (neutrinos not shown in figure)
http://csep10.phys.utk.edu/astr162/lect/energy/cno.html

3.3 NUCLEOSYNTHESIS BEYOND HYDROGEN

Stars more massive than the Sun have higher core temperatures, and can continue the fusion of light elements after all hydrogen is consumed. This is possible as long as the fusion of progressively heavier elements is exothermic, where fusing lighter nuclei to heavier nuclei releases energy. This fusion process can continue until binding energy reaches a maximum with the formation of iron.

CNO helium burning creates carbon. At core temperatures approaching 6 x 10^8 K, carbon fuses into oxygen, neon, sodium and magnesium. At 10^9 K the oxygen fuses to magnesium, silicon, phosphorus and sulfur. The process can continue only until iron and nickel are formed. Up to this point the fusion processes released energy. The creation of heavier elements requires the input of energy, the energy of supernova. Figure 12 illustrates the fusion progression of massive stars.

There a basically two types of supernovae. Type Is occur in a binary system consisting of a white dwarf and star. As the white dwarf draws matter from the star, it explodes into a supernova when its mass exceeds a critical level. In a type II supernova, the formation of iron and nickel stops the exothermic fusion process and the star collapses under its own gravity. The infalling material bounces from the dense iron-nickel core, and causes an explosion which creates a fast outward-moving shock wave. This supernova energy creates the elements more massive than iron in the Periodic Table.

The existence of such elements in our solar system is due to the remnants of supernovae which occurred prior to our solar system's formation.

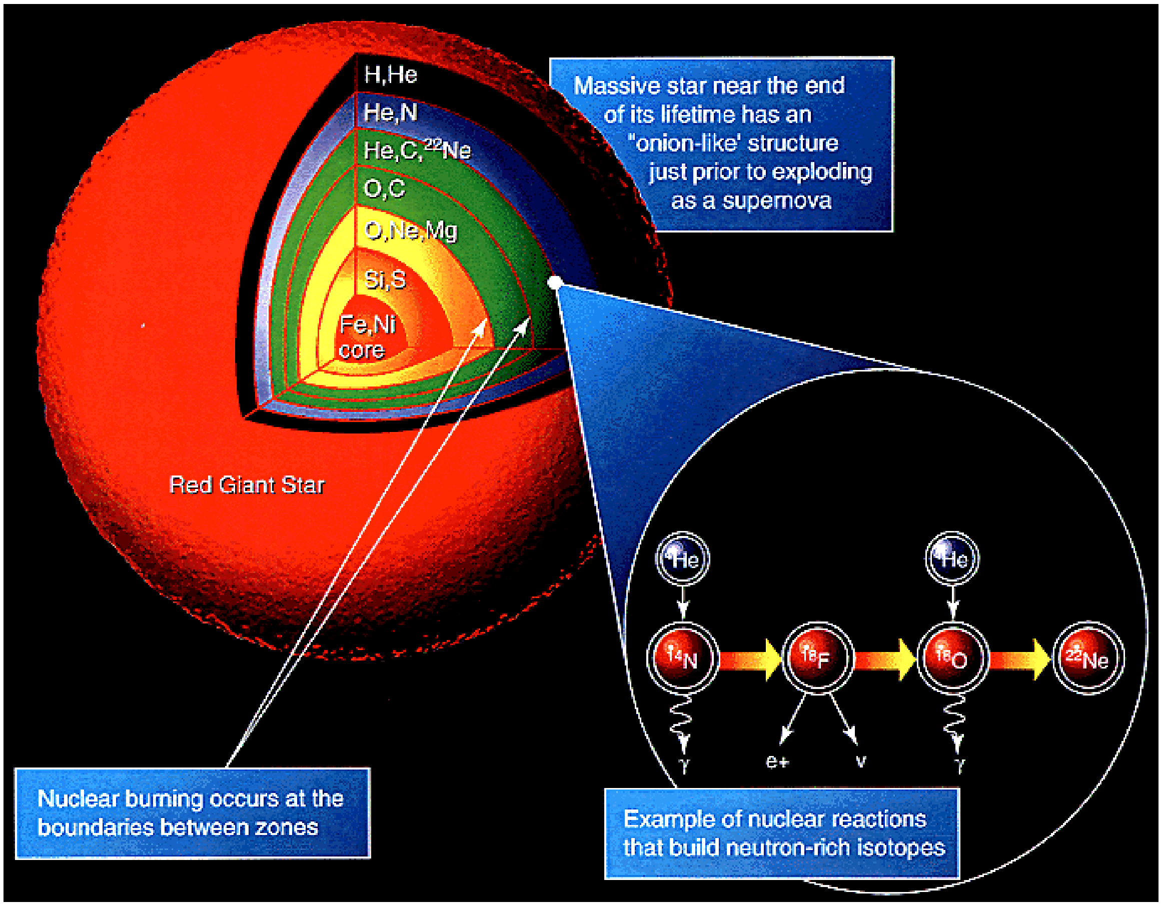


Figure 12. Fusion Progression in Massive Stars Prior to Supernova
http://helios.gsfc.nasa.gov/nucleo.html

4. PARTICLE ACCELERATORS

In the previous section on "Pair Production and Pair Annihilation," there was a discussion on the equivalence of mass and energy. It should be obvious that higher energetic particle accelerators are capable of creating more massive particles than accelerators of lower energy. This is one of the reasons for creating the Large Hadron Collider and its quest for the Higgs boson and theoretically massive supersymmetric particles.

4.1 SOME ACCELERATOR HISTORY

Variations of particle accelerators have been around since the end of the nineteenth century. William Roentgen discovered x-rays in 1895 via accelerated electrons from cathode-ray tubes. Prior to the on-going migration to flat panel screens many television sets were cathode-ray tube based. The use of electric potentials to move charged particles in nuclear physics was an early type of particle accelerator. Current accelerator devices like Van de Graaf machines have potentials of 25 MeV. There are limitations to creating electrostatic accelerators at higher energies due to safety issues at such high voltages.

The earliest accelerator devices utilizing magnetic forces were cyclotrons, in which circular particle paths were employed. In 1931, E. O. Lawrence (1901- 1958) achieved 1.0 MeV energies with his 11 inch diameter cyclotron. His device used a circular magnetic field plus an alternating electric field to accelerate ions (Figure 13). The next step for higher energies was the development of synchrotrons, in which the magnetic and electric fields gradually change as ions approach the speed of light and gain mass. The current most powerful synchrotron is the Fermilab Tevatron, which achieves energies approaching 2.0 TeV (2 x 10^{12} eV). Beams of protons and antiprotons travel in opposite directions in a 1.27 km radius circular path. Detectors are positioned at the collision points of the two particle beams to assess the generated activity.

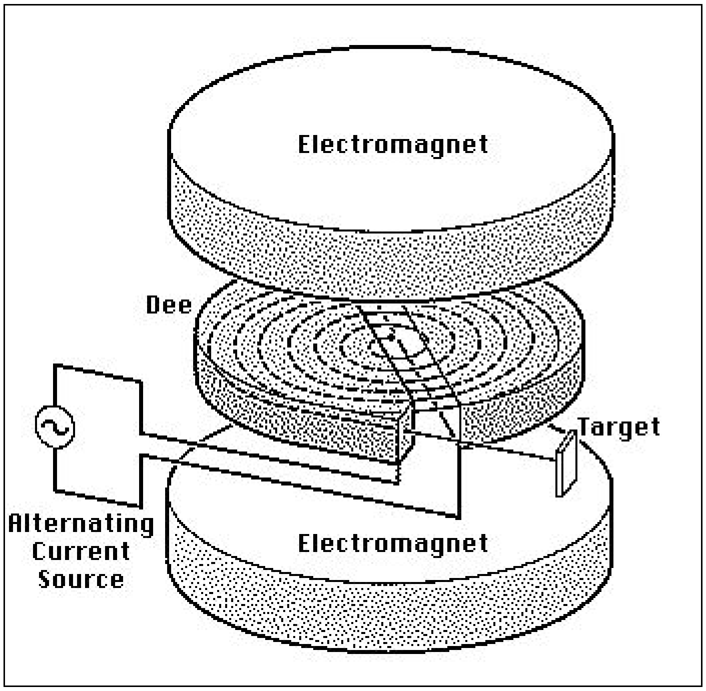


Figure 13. Basic Cyclotron Schematic
http://www.hcc.mnscu.edu/programs/dept/chem/abomb/Cyclotron_Diagram.jpg

4.2 ACCELERATOR RESOLUTION

We can compare the “seeing” capability of a particle accelerator at the atomic nucleus level to our ability to see detail with the finest optical microscope. Assume we’re looking at something in 500 nm light. This allows us to see small objects in our microscope in the range of 0.5 x 10^{-6} meters. Significantly smaller details would not be resolvable in 500 nm light.

Quantum theory shows that particles have a wave nature, matter waves. Louis de Broglie (1892-1987) proved that matter wavelengths were inversely proportional to momentum:

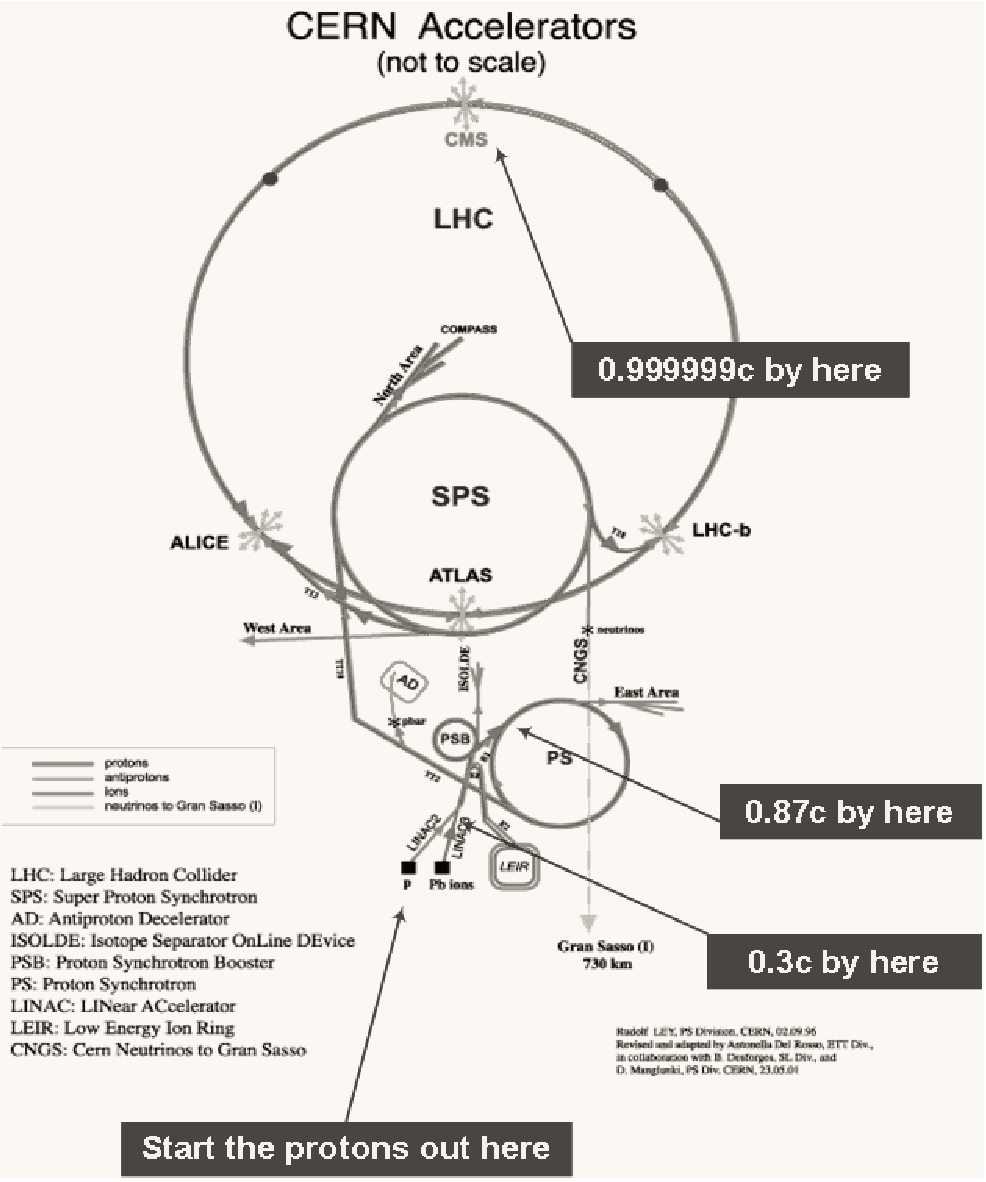
$$\lambda = {}^{h}\!/_{p} \tag{3}$$

Where λ is the matter wavelength in meters, h = 6.626 x 10 $^{-34}$ Js (Planck's constant), and p is the particle's momentum. We don't perceive matter waves for ordinary objects because their wavelengths are so small. We can't see the diffraction or interference associated with waves like visible light. For example, a 5 ounce baseball moving at 60 miles/hour has a de Broglie wavelength of only 1.7 x 10^{-34} meter, which is totally impossible to detect. On the other hand, an electron with 150 keV energy has a wavelength of 0.1 nm, five thousand times more resolution than ordinary light. Electron waves are the basic mechanism behind high resolution in electron microscopes. The higher the energy of a particle accelerator, the better its resolution and the better its ability to probe deeper into a nucleus. The upcoming Large Hadron Collider (LHC) will be capable of producing a total energy of 14 TeV (1.4 x 10 ^{13} eV) for its colliding protons, which results in de Broglie wavelengths and resolution of 8.86 x 10^{-20} meters. The size of a nucleus is approximately 10^{-15}m. The LHC will probe details almost a million times smaller than an atomic nucleus. The temperature at 14 TeV is about 1.65 x 10^{17} K, which is equal to that experienced about a picosecond after the Big Bang. Cosmology astrophysicists will gain insights on conditions just after the creation of the universe via the LHC and physicists expect many new areas in particle physics to be discovered over the next decade.

4.3 LARGE HADRON COLLIDER (LHC) OVERVIEW

The CERN LHC is due for startup on September 10, 2008. Initially, it plans to run each of its two beams of protons at 5 TeV. Maximum energy operation is planned early in 2009. This device will be the most powerful particle accelerator in history, with colliding proton energy of 14 TeV. The 27 km circular tunnel was originally used by CERN's LEP, an electron/positron collider whose energy exceeded 200 GeV. The 3.8 meter diameter tunnel is buried 50 to 175 meters underground. The tunnel contains two beam pipes. One pipe has a proton beam going in one direction, while the other has a proton beam going in the other direction. The vacuum pressure in the beams is 10^{-13} atmospheres to minimize collisions with gas molecules. Each beam's energy is 7 GeV, and the energy at the two beam's collision point would be 14 GeV. A series of 1,232 dipole magnets keeps the particles moving in a circular path, while 392 quadrapole magnets keep the beams focused. It's expected that the LHC will generate 6 x 10^{8} particle collisions per second. To minimize electrical energy, the magnets are kept at temperatures of only 1.9 K, allowing superconductive operation.

The protons are energized in four stages prior to attaining their final 7 TeV energy. First, a linear accelerator (Linac 2) achieves 50 MeV energy. Second, a Proton Synchrotron Booster (PSB) produces 1.4 GeV energy. Third, the Proton Synchrotron accelerates to 26 GeV. Finally, the Super Proton Synchrotron reaches 450 GeV. The LHC provides the ultimate 7 TeV energy for each beam. Figure 14 illustrates the stage and detector schematic.



0.999999c by here

0.87c by here

0.3c by here

Start the protons out here

Figure 14. Large Hadron Collider Schematic
http://lhc-machine-outreach.web.cern.ch/lhc-machine-outreach/images/complex/Cern-complex.gif

Six detectors in the LHC will conduct a variety of experiments. ATLAS and CMS are general purpose detectors. ALICE will be used for studying heavy ion (lead) collisions. The other three (LHCb, LHCf and TOTEM) are for specialized use. The role of particle accelerator detectors is to time stamp each collision event along with data on total energy, momentum, velocity, and charge. Sophisticated software is designed to flag and save events of interest. The dimensions of ATLAS give some idea of the scope and complexity of a detector. It consists of a series of four ever-larger concentric cylinders around the collision point of the two beams. This detector is 148 feet long, 148 feet wide and 82 feet high with a weight of 7,700 tons. ATLAS is the collaboration of 1,900 physicists from 35 countries. Areas of research for ATLAS will include the mystery of dark energy and dark matter. Figure 15 illustrates the internals of ATLAS during construction.

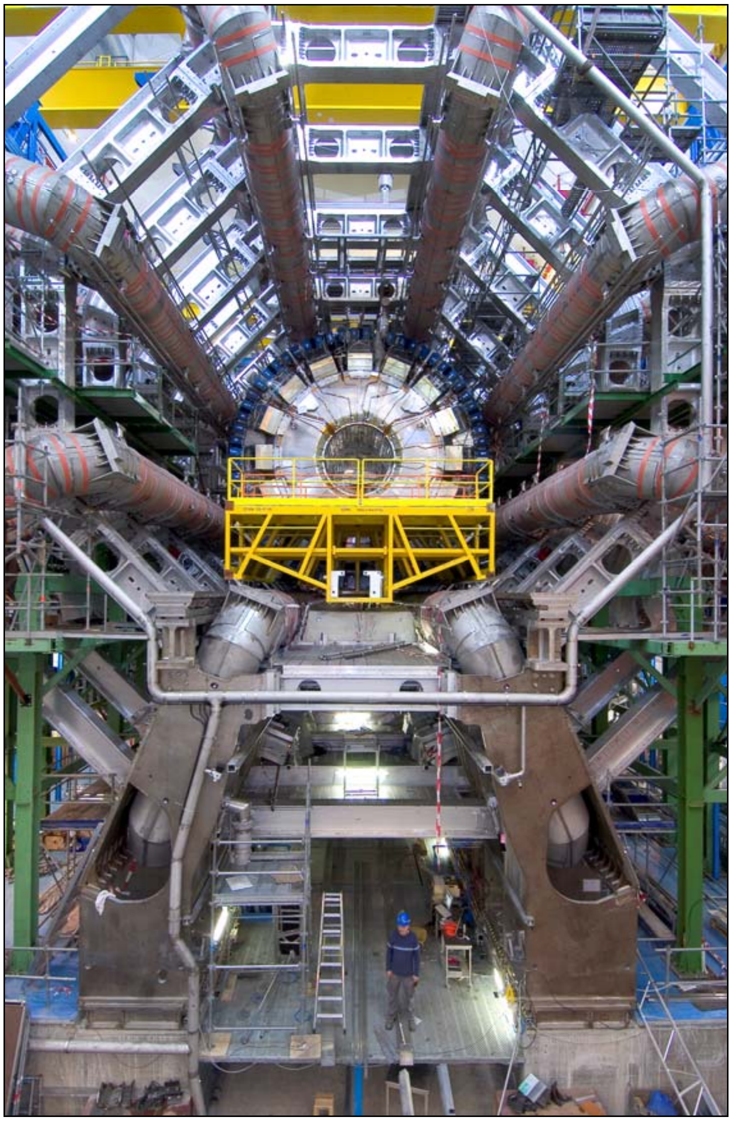


Figure 15. The LHC's ATLAS Detector
http://www.w3.org/DesignIssues/diagrams/cern/csCERN2.jpg

4.4 SOME LHC RESEARCH AREAS

The Higgs Boson

Mass has been a puzzle in particle physics. Photons are massless and quarks are more massive than electrons. The Standard Model of particle physics developed a theoretical mechanism for particle mass in the 1960s. Prior theories had predicted that quarks and leptons should be massless. A number of scientists, but Peter Higgs (1929-) in particular, postulated the existence of a particle whose field is the origin for elementary particle mass. This Higgs boson has so far been unsuccessfully sought for several years by Fermilab's Tevatron accelerator and will be the LHC's prime target. Current thinking is that the Higgs particle has a mass between 100-200 times that of a proton, with zero charge and spin.

To create the Higgs, when two protons collide, the energy and charge of the particles created are measured by the LHC detectors. The Higgs boson is unstable, and its decay products change depending on its mass. It's thought that a Higgs particle would be signaled by the detection of top/antitop or bottom/antibottom quark pairs, or paired Z^0 bosons. These in turn decay into lighter particles like leptons. It's expected that a Higgs boson may be created every few hours, but several years of statistics will be necessary for confirmation. Given the high interaction rates (luminosity) and energies between the LHC's colliding protons, it's hoped that the LHC will successfully detect Higgs.

Dark Matter and Supersymmetry

The universe is made of matter (24%) and energy (76%). However, only 4% of the universe appears to be the ordinary baryonic matter that responds to the four forces of nature. Dark matter seems to respond only to gravity. Dark matter resulting from our universe's creation is some strange stuff, that doesn't behave the way matter we're familiar with does. Dark matter doesn't absorb or reflect light nor does it appear to have electric charge. Dark matter particles move much slower than the speed of light and are called "cold" dark matter or weakly interacting massive particles (WIMPs). A common theory of dark matter is that it's composed of a *supersymmetry* particle. An Italian research group (DAMA/LIBRA) announced a possible detection of dark matter in April, 2008 but their findings haven't been verified by other organizations.

Thirty years ago scientists postulated that the two types of matter, fermions (spin ½ particles like quarks and leptons) and bosons (integer spin particles like photons and gluons) had super-partners. These partners were more massive and had opposite spins. Thus the partner of a neutrino (spin ½) is called a *neutralino* (spin 0) and is much more massive than a neutrino. As of now, no supersymmetric particles have been detected. This isn't surprising since they are so massive that only the highest energy accelerators might create them. Also, the most massive super-partners decay rapidly. At Big Bang creation, only the lightest super-partner, the neutralino was stable enough to have survived to today.

It is hoped that the high energy attainable in the LHC can create supersymmetric particles. Since this type of matter is so non-reactive, scientists will examine collision events that create asymmetric energy/momentum balances that might indicate escaping supersymmetric particles. If the mass of a stable neutralino is in the order of that of 50 protons, it would be a candidate for the dark matter that is detectable only by its gravitational effects. The detection of supersymmetry by the LHC would be of great interest to string theorists as well as to the astronomical community. Supersymmetry is integral to string theory, relating the particles that transmit forces to those that make up matter.

5. FINAL THOUGHTS

Late in the twentieth century the relationship between astronomers and particle physicists strengthened as research into the Big Bang accelerated. Physicists use the universe as a laboratory to explain particle phenomena, and astronomers use the laboratory to explain cosmology phenomena. The mysteries of dark energy and dark matter, key to astronomer understanding of the universe relate to questions physicists investigate with particle accelerators. As new findings are revealed via the LHC, we may learn whether dark matter has been identified, whether the Higgs particle exists, and whether string theory's supersymmetry can be confirmed. The next decade will be an exciting time for science.

6. REFERENCES

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